

# **SIMULTANEOUS SIMULATION OF BUILDINGS AND MECHANICAL SYSTEMS IN HEAT BALANCE BASED ENERGY ANALYSIS PROGRAMS**

by

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## **SUMMARY**

The current generation of building simulation software is based upon separate building and mechanical system and equipment simulations. This scheme evolved primarily because of memory limitations of the computers which were used to develop the programs. These limitations are no longer important so the separate building and system scheme needs to be reevaluated. This paper will specifically discuss experience resulting from introducing simultaneous system simulations into the BLAST program.

BLAST currently uses a linear univariate control profile to describe the heating and cooling provided by the fan system as a function of room temperature during the loads calculation part of the simulation. Control profiles for each thermal zone are used to model the system response during the system simulation. This model of the fan system works very well for systems that provide amounts of heating or cooling that are dependent only on zone temperature. When the output of the fan system is affected by the outdoor temperature or conditions in other zones, the control profile model is no longer adequate. The conditions in the zones must be known in order to calculate the system output, but the system output must be known in order to calculate the conditions in the zones. So a more sophisticated representation of the mechanical systems is needed.

This paper specifically discusses the results of doing a complete system simulation within the loads calculation portion of the program by using a shortened time step combined with lagging the two parts of the simulation. The effects of time step length on accuracy and computation time are presented.

## **I. INTRODUCTION**

In current building energy analysis programs which are capable of simulating a building and its mechanical systems for an entire year, there are two primary methods in use: the heat balance method and the weighting factor method. In either case, such simulations are capable of providing a

detailed breakdown of hourly building energy use. The Building Loads Analysis and System Thermodynamics (BLAST) program uses the heat balance method and has been employed as a 'testbed' program for various methods of integrating the building-mechanical system simulation.

In the current version of BLAST the building, its air handling systems, and its equipment are simulated sequentially with no feedback, i.e. the building conditions are fed to the air handling system to determine its response but that response is not then allowed to affect the building conditions. This simulation technique works well when the system response is a well-defined function of the air temperature of the conditioned space. But in situations where the system is dependent on outside conditions and/or other parameters of the conditioned space the lack of feedback from the system to the building can lead to unphysical results, i.e. if the system provides too much cooling to a conditioned space the excess cooling is reported by BLAST as 'overcooling', instead of showing the decrease in conditioned space temperature that would actually occur. If the three parts of the BLAST simulation could be performed simultaneously, all possible interactions could be taken into account.

Previous work in this area has been reported by Witte, et al. [1] who tried several approaches to modelling building-fan system interactions. These techniques included successive substitution with a damping factor to prevent excessive oscillation of the system response and zone temperature, and a Newton-Raphson iteration technique to drive the sum of the fluxes to zero. Both methods were implemented, but at significant additional computational cost over the standard BLAST program. Modifying the BLAST program to accept time steps shorter than one hour has enabled the additional work described in this paper which focuses on eliminating iterations from the simulation loop.

## II. CURRENT METHOD - HOURLY ENERGY BALANCE

BLAST currently has three main sections which together provide a complete simulation of a building, its fan systems and its equipment. The loads simulation models all the heat transfer into or out of each building zone through the zone surfaces due to conduction, convection and radiation, which is assumed to consist of longwave (infrared) and shortwave (visible) components. In addition, the loads simulation can model the effects of people, lighting, and equipment within the zone, adjacent zones on each other due to conduction through zone walls and mixing of zone air, and infiltration of outside air into the zone. The air handling systems which condition each zone are simulated in the fan systems simulation, which determines the supply airflow volume flow rate and temperature needed to maintain the zone at the desired temperature. It is in this part of the simulation that the effects of outside conditions on system component operation are taken into account. Finally the central plants simulation models the chillers, boilers, etc which serve the fan systems.

In the current structure of BLAST these three sections operate somewhat independently in that information is passed from the loads simulation to the fan system simulation to the central plants simulation but there is no information transfer in the other direction. BLAST first performs the loads simulation by computing an hourly energy balance for each zone using weather, scheduled loads (lights, people, etc.) and desired zone conditions. This energy balance is represented as follows:

$$Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T_{out} - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) + Q_{sys} = C \quad (1)$$

where  $Q_c$  is the sum of the internal loads,  $\sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z)$  represents convective heat transfer from the zone surfaces,  $\dot{m}_{inf} c_p (T_{out} - T_z)$  is infiltration of outside air,  $\sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z)$  represents interzone air mixing, and  $Q_{sys}$  represents the system output. Internal loads occur when lighting, electrical equipment, people, etc. are present in the zone and as such are specified in input. Heat transfer through zone surfaces is computed from the surface convection coefficient  $h_i$  and the surface temperature  $T_{si}$ , where each surface or surface element (wall, window, door, etc.) is assumed to be isothermal. The surface temperatures are computed by performing heat balances on the inside and

outside surfaces, and using conduction transfer functions to relate conditions across the surface. Sources of infiltration are doors and windows open to the outside environment, in BLAST infiltration rates are specified in input. Similarly, the mixing term represents infiltration of air from other zones in the building and is likewise specified in input. More detailed descriptions of the computational procedure used in BLAST and the method of conduction transfer functions can be found in references [2] and [3]. Finally, since the system is not simulated at this point  $Q_{sys}$  is computed using a control profile, which is a piecewise linear approximation of the system output as a function of zone mean air temperature ( $T_z$ ):

$$Q_{sys} = m T_z + b \quad (2)$$

where  $m$  is the slope of a linear segment in the control profile and  $b$  is the segment endpoint. The desired zone temperature is achieved by using line segments with different slopes to manipulate the shape of the control profile. A generic single segment control profile is shown in figure (1).

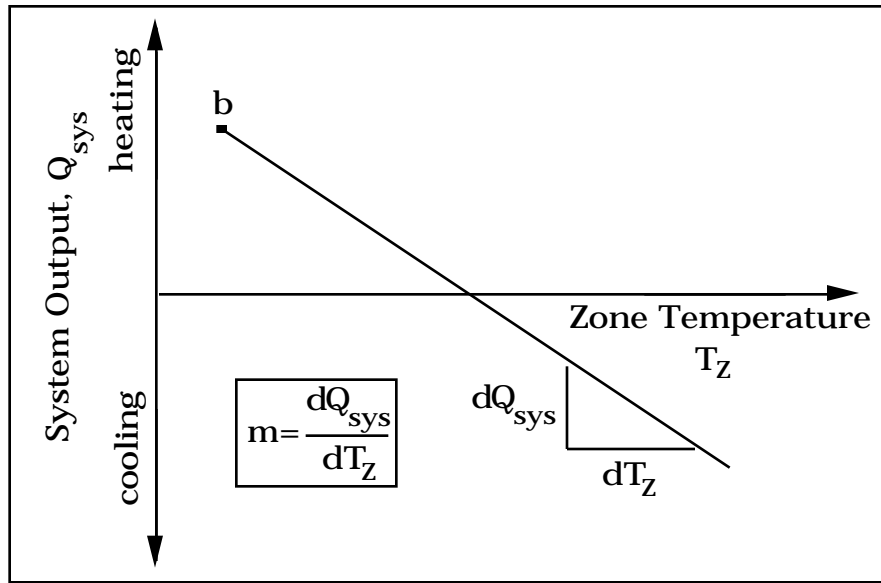


Figure 1: Generic single segment BLAST control profile

Substituting equation (2) into the zone energy balance equation and solving for the zone temperature gives:

$$T_z = \frac{Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + b}{\sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p - m} \quad (3)$$

BLAST iterates on this equation until the change in  $T_z$  is less than some tolerance value at which point the simulation stores the zone conditions and the system output as calculated by the control profile and goes on to the next time step. At the end of the loads simulation, which can be performed for a "design" day or for an entire year, the information computed by the loads simulation is used in fan systems. The fan systems simulation then attempts to match the required  $Q_{sys}$  every hour, based on zone and outside conditions. This technique works very well when the system output is dependent on  $T_z$  alone; however, when the system output is also a function of the outside conditions or conditions

in the zone other than  $T_z$ , a single control profile is no longer an adequate representation of the system-zone interaction. In the current structure of BLAST, when the system does not fulfill the zone conditioning demands, either by over- or under-conditioning the zone, this is reported as an 'unmet load'. The effects of this unmet load on the zone, such as reduced or elevated zone temperature, are not calculated. Once the fan systems simulation is complete, BLAST repeats the process for central plants where similar problems with 'unmet loads' can arise.

### III. DISCUSSION OF METHODS AVAILABLE

Previous work by Witte, et al. [1] discusses in detail the implementation of Newton-Raphson and successive substitution techniques in BLAST. Both of these methods involve iterating each time step to drive the residual of the heat balance equation (Newton-Raphson) or the change in zone air temperature (successive substitution) to zero. The methods discussed in this paper all use information from previous time steps to predict system response and in this sense they can all be thought of as time marching methods requiring no iteration. In order to preserve the stability of the simulation a shorter time step than one hour is required; therefore, some of the benefit of eliminating iterations is lost in the increased number of computations required for the same simulation time.

The basic lagging method results when the right hand side of equation (3) is evaluated using information from the previous time step. The control profile is replaced by the actual system response which is calculated using previous zone and outside conditions. The zone air capacitance is not included:

$$T_z^t = \left( \frac{Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + Q_{sys}}{\sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p} \right)^{(t-t)} \quad (4)$$

Thus the system output lags the zone loads by one time step, although the time step does not explicitly appear in the formulation. This last point is important since it implies that the stability of the scheme may not be strongly dependent upon the time step. Additionally, for most systems simulated in BLAST, it is possible to formulate  $Q_{sys}$  using the mass flow provided by the system and the temperature of the supply air:

$$Q_{sys} = \dot{m}_{sys} c_p (T_{supply} - T_z) \quad (5)$$

Note that this expression is also a function of the zone air temperature. We now substitute for  $Q_{sys}$  in the heat balance equation and collect terms containing  $T_z$  as before. The resulting expression for the zone air temperature using the lagging method is as follows:

$$T_z^t = \left( \frac{Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + \dot{m}_{sys} c_p T_{supply}}{\sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p + \dot{m}_{sys} c_p} \right)^{(t-t)} \quad (6)$$

The zone energy balance expressed as equation (1) can be reformulated so that instead of the difference of loads and system output being set to zero to provide an exact balance, the zone air capacitance is introduced so that the difference represents the change in energy storage in the zone air. This storage is given by the product of the zone air capacitance and the first derivative of the zone air temperature:

$$C_z \frac{dT_z}{dt} = Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) + \dot{m}_{sys} c_p (T_{supply} - T_z) \quad (7)$$

It should be noted here that it may be appropriate to define  $C_z$  as the zone total capacitance which includes contributions from fast responding mass within the zone in addition to the zone air. The derivative term can be computed using finite difference approximations such as:

$$\left. \frac{dT_z}{dt} \right|_t = \left( \frac{1}{\Delta t} \right) (T_z^t - T_z^{t-\Delta t}) + O(\Delta t) \quad (8)$$

which is first order accurate in time and is more commonly known as the Euler formula. The use of finite differences in a long time simulation such as BLAST may cause some concern due to the build-up of truncation error, especially when the finite difference approximation is of low order. However, the cyclic nature of the simulations will cause truncation errors to cancel over one cycle so that there will be no accumulation over the long term (Walton [4]). The finite difference expression for the zone air temperature using the Euler approximation is given by:

$$C_z \frac{T_z^t - T_z^{t-\Delta t}}{\Delta t} = \left( Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T_{inf} - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) + \dot{m}_{sys} c_p (T_{supply} - T_z) \right) \Delta t \quad (9)$$

Solving explicitly for  $T_z^t$  gives the new zone air temperature in terms of conditions at the previous time step:

$$T_z^t = T_z^{t-\Delta t} + \frac{\Delta t}{C_z} \left( Q_c + \sum_{i=1}^{nsurfaces} h_i A_i (T_{si} - T_z) + \dot{m}_{inf} c_p (T_{inf} - T_z) + \sum_{i=1}^{nzones} \dot{m}_i c_p (T_{zi} - T_z) + \dot{m}_{sys} c_p (T_{supply} - T_z) \right) \Delta t \quad (10)$$

It is well known that the Euler method becomes less accurate and eventually unstable as the time step is increased. However, it is the size of  $\frac{\Delta t}{C_z}$  which determines the stability of the simulation. Thus, the larger the zone capacitance, the longer the allowable time step before instability is observed. In effect the zone capacitance provides damping to absorb excess system output. However, even for a reasonably large zone the capacitance can be small and large changes in the zone air temperature can occur, leading to instabilities in the simulation.

The finite difference method may be modified by grouping all the terms containing the zone air temperature on one side of the equation and the remaining terms on the other:

$$C_z \frac{T_z^t - T_z^{t-\Delta t}}{\Delta t} + \sum_{i=1}^{nsurfaces} h_i A_i T_z^t + \dot{m}_{inf} c_p T_z^t + \sum_{i=1}^{nzones} \dot{m}_i c_p T_z^t + \dot{m}_{sys} c_p T_z^t = \left( Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T_{inf} + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + \dot{m}_{sys} c_p T_{supply} \right) \Delta t \quad (11)$$

Thus the explicit appearance of the zone air temperature is removed from one side of the equation. Dividing through by the coefficient of  $T_z$  gives an energy balance equation similar to the lagging method which includes the effects of zone air capacitance:

$$T_z^t = \frac{\left( \frac{C_z}{t} T_z + Q_c + \sum_{i=1}^{nsurfaces} h_i A_i T_{si} + \dot{m}_{inf} c_p T + \sum_{i=1}^{nzones} \dot{m}_i c_p T_{zi} + \dot{m}_{sys} c_p T_{supply} \right) (t - t)}{\left( \frac{C_z}{t} + \sum_{i=1}^{nsurfaces} h_i A_i + \dot{m}_{inf} c_p + \sum_{i=1}^{nzones} \dot{m}_i c_p + \dot{m}_{sys} c_p \right)} \quad (12)$$

To avoid confusion with the finite difference method described previously we will call this method "lagging with zone air capacitance."

In addition to equation (8) which resulted in the formulation given by equation (12), there are numerous ways of expressing the first derivative of the temperature in finite difference form. By using Taylor series expansion methods it is possible to develop higher order expressions for the first derivative with corresponding higher order truncation errors. The following are second, third, fourth, and fifth order finite difference approximations, respectively, of the first derivative of the zone air temperature with respect to time:

$$\begin{aligned} \frac{dT_z}{dt} \Big|_t &= (t)^{-1} \left( \frac{3}{2} T_z^t - 2T_z^{t-t} + \frac{1}{2} T_z^{t-2t} \right) + O(t^2) \\ \frac{dT_z}{dt} \Big|_t &= (t)^{-1} \left( \frac{11}{6} T_z^t - 3T_z^{t-t} + \frac{3}{2} T_z^{t-2t} - \frac{1}{3} T_z^{t-3t} \right) + O(t^3) \\ \frac{dT_z}{dt} \Big|_t &= (t)^{-1} \left( \frac{25}{12} T_z^t - 4T_z^{t-t} + 3 T_z^{t-2t} - \frac{4}{3} T_z^{t-3t} + \frac{1}{4} T_z^{t-4t} \right) + O(t^4) \\ \frac{dT_z}{dt} \Big|_t &= (t)^{-1} \left( \frac{137}{60} T_z^t - 5T_z^{t-t} + 5 T_z^{t-2t} - \frac{10}{3} T_z^{t-3t} + \frac{5}{4} T_z^{t-4t} - \frac{1}{5} T_z^{t-5t} \right) + O(t^5) \end{aligned} \quad (13)$$

Observe that as the order of the approximation increases, the number of previous temperatures required increases and the dependence on the most recent temperature decreases. The higher order derivative approximations have the potential to allow the use of larger time steps by smoothing transitions through sudden changes in zone conditions. Use of these approximations in equation (7) results in forms similar to equation (12), and these were included in this investigation.

In summary, table 1 shows the methods implemented in BLAST and the equations which correspond to these methods:

METHOD	FORMULA
Finite difference	Equation (9)
lagging	Equation (6)
lagging with capacitance	Equation (12) and variations based on Equations (13)

Table 1: Combined methods implemented in BLAST and corresponding equations

#### IV. IMPLEMENTATION OF METHODS

A special development version of BLAST has been created which incorporates the ability to select a desired heat balance option from the methods described above. This readily allows direct comparisons between methods to be made. That the Newton-Raphson and damped successive substitution methods can be used to model the loads/system interaction with one hour time steps has been demonstrated by Witte et al. [1], however, both methods incur significant computational penalty over the standard version of BLAST. Additional work with the lagging technique at a one hour time step demonstrated the unstable nature of the solution. The standard version of BLAST is unable to handle time steps other than one hour. The development version was therefore modified so that the time step is user definable. This has enabled subsequent methods to be tested at time steps as small as 5 minutes. The lower limit on the time step occurs because the number of conduction transfer functions required to calculate the surface heat fluxes grows rapidly as the time step is decreased; and, especially for heavy constructions, this growth in number also increases the error incurred in conduction transfer function calculations. Ultimately, the errors grow to a point where the wall flux calculations will not converge.

The lagging method without zone air capacitance proved to be quite unstable regardless of time step. This was not entirely unexpected since the time step dependence only appears through the change in outside conditions and scheduled internal loads as the simulation progresses. More importantly, the stability of the method depended upon the capacity of the system with respect to the zone loads. This meant that in order to guarantee a stable simulation the system had to be undersized compared to the zone's conditioning requirements. Further analysis showed that the simulation would, in general, be unstable when the slope of the system response as plotted against the zone air temperature was steeper than the slope of the zone loads. The principal reason for the observed instabilities seems to be the lack of damping to 'absorb' excess conditioning provided to the zone by the system. This overcompensation can occur when the system is oversized in comparison to the zone loads or when the slope of the system output is steeper than the slope of the zone load as a function of  $T_z$ .

The finite difference method was applied successfully to BLAST, however the simulation did become unstable after the time step was increased beyond about 6 minutes for a 20'x20'x10' zone. In comparison the modified finite difference method with higher order derivative approximation could be made to run stably at time steps of up to one half hour for the same case. It should be noted that in practice time steps of 6 - 10 minutes will be required to reduce or eliminate oscillations in the zone mean air temperature ( $T_z$ ) which occur due to changes in the internal loads or system operation. For

example, a zone may only require conditioning during the hours of 8 a.m. to 5 p.m. For the rest of the day the zone is not conditioned and the temperature is allowed to float. Additionally, lights and electrical equipment, represented in BLAST by internal loads, within the zone may only operate from 8 a.m. to 5 p.m. Thus the simulation would see large changes in the zone loads and system output at 8 a.m. and 5 p.m. causing  $T_z$  to oscillate, possibly for several time steps after the event occurs. This 'ringing' effect is due to the fact that the simulation can only sample and control  $T_z$  at discrete intervals and it updates  $T_z$  based on previous conditions. Thus there is a tendency to undercompensate for changes occurring over a short span of time.

Current BLAST output is reported at hourly intervals and even with the implementation of a short time step method one hour remains the most convenient unit of time for reporting energy usage. In order to get output in the hourly format and account for information from the intermediate times, hourly averages are computed by multiplying by the time step and summing each time until the next hour is reached. This averaging process does of course cause the detailed time step information to be lost, and also smooths out oscillations. This can be a disadvantage since it masks instabilities in the computational method.

## V. RESULTS COMPARED WITH BLAST

Comparison of the three methods under consideration has been accomplished by simulating a building containing a single zone of dimensions 20'x 20'x 10' (6.1m x 6.1m x 3.05m) through a summer design day at Chanute AFB, Rantoul, Illinois, USA. In addition to the loads generated on the zone by fluctuations in outside conditions, the zone is subject to 10 KBtu/hr (2.93 kW) additional heating due to electrical equipment within the zone. This internal load operates from 8am to 5pm.

In figures 2a, 2b, and 2c, BLAST is compared to the finite difference scheme, the lagging method, and lagging with zone air capacitance which all use a time step of 0.1 hours (6 minutes). It should be noted that comparisons of standard BLAST, which does separate simulations for the building and fan system, with the above methods, where the simulations are combined, are somewhat qualitative since BLAST does not account for the operating characteristics of the system in the loads simulation. Figure 2a plots the temperature history of the conditioned space. For this case BLAST gives a constant temperature of 73 F (22.8 C), while the other methods show a temperature which fluctuates over the day. While agreement between the combined methods is good over parts of the simulation, discrepancies are apparent. These can be explained by figure 2b which plots the sum of the absolute values of the change in temperature of the conditioned space in each time step, averaged over the hour. In figure 2b, the lagging with capacitance method shows two small peaks at hours 8 and 18 where the internal load turns on and off respectively. These peaks represent the sharp change in zone air temperature which is a result of the change in internal load. The other two methods show much larger peaks at hours 8 and 18, and these peaks continue for several time steps. Since the average temperature in figure 2a does not show any large excursions, the implication is that the temperature on the short time scale of the calculations is oscillating considerably after the changes in internal load occur. The finite difference method is clearly the worst of the three methods with a peak-to-peak temperature oscillation of about 14 F (7.8 C). Figure 2c plots the cooling energy required to maintain temperatures to those shown in figure 2a. However, the combined methods plots are actual system cooling provided to the zone, while the BLAST plot is of the cooling required to maintain a zone air temperature of 73 F.

Figures 3a, 3b, and 3c are a similar sequence to 2a, 2b, and 2c, but in these plots we are comparing versions of the lagging with capacitance method which incorporate different order approximations for the derivative term. Figure 3a, which is the zone temperature history, and figure 3c, which is the cooling load history, indicate good quantitative agreement between the five methods. The only significant discrepancies occur at the first and fifth orders and this is further born out by figure 3b which indicates that considerable temperature oscillation is occurring. The third order method has the smallest tendency to oscillate.

Figures 4a, 4b, and 4c are the same sequence of plots as before: however in this case we have implemented the third order method at time steps of 1/2 hour, 1/4 hour, 1/6 hour, and 1/10 hour.

Figures 4a and 4c show good quantitative agreement and only by looking at figure 4b do we see that some temperature oscillation is occurring at 1/2 hour. The reduction in the size of the peaks is due primarily to the decrease in time step since the change in temperature per time step required to effect the same total change over the hour decreases as more time steps are taken per hour: i.e. as the time step is reduced.

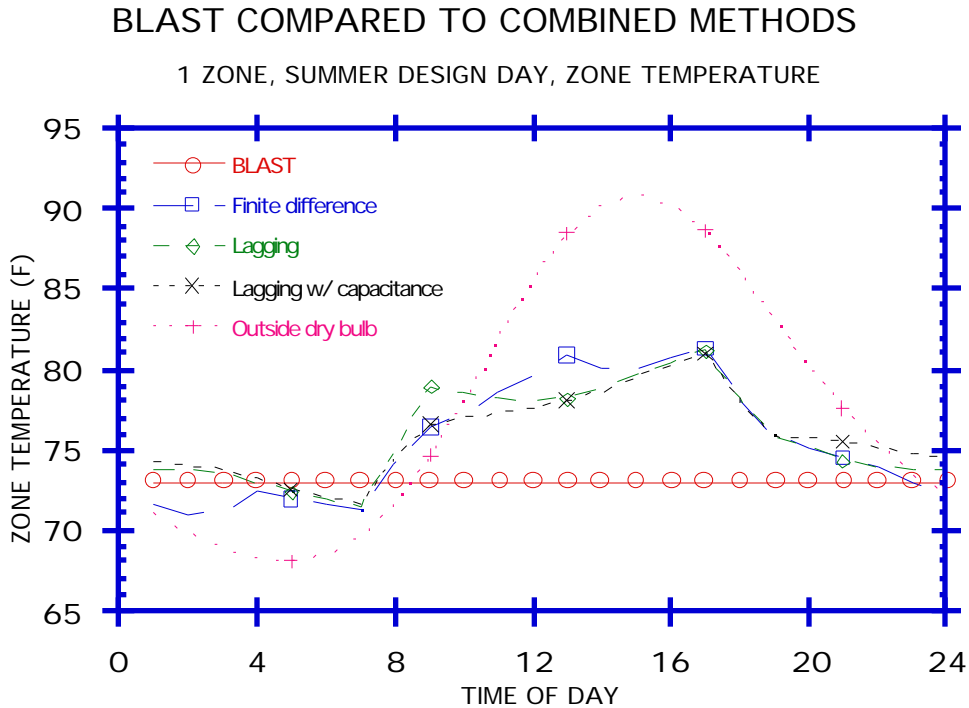


Figure 2a: Zone air temperatures as computed by BLAST and combined methods

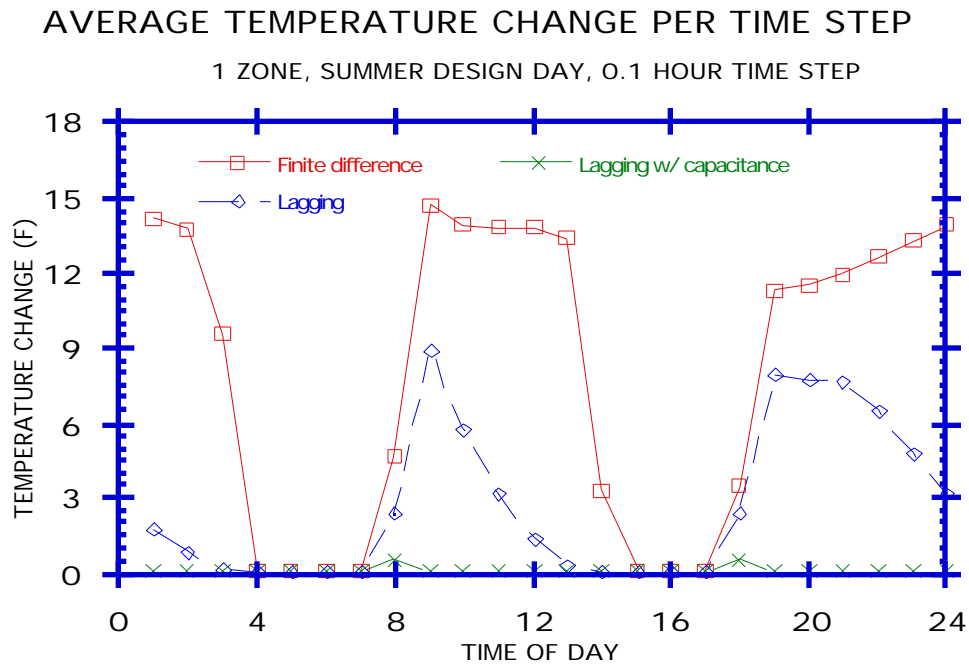


Figure 2b: Average change in zone air temperature per time step for finite difference, lagging and lagging with capacitance methods at 1/10 hour time step.

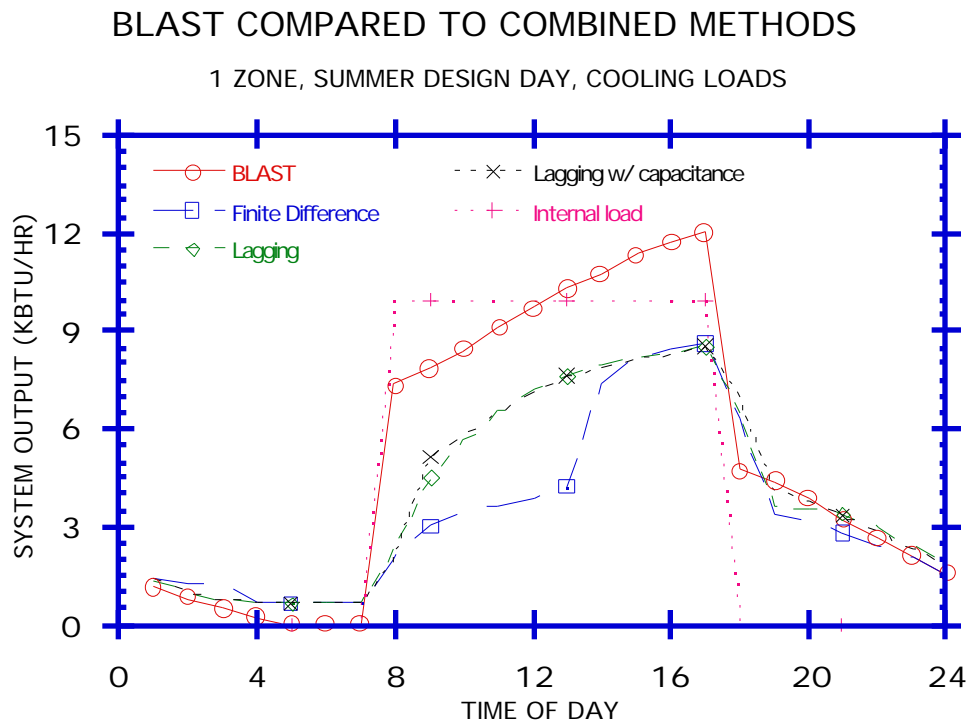


Figure 2c: Zone cooling loads as computed by BLAST and combined methods

## EFFECTS OF ORDER OF DERIVATIVE APPROXIMATION

1 ZONE, SUMMER DESIGN DAY, 0.25 HOUR TIME STEP

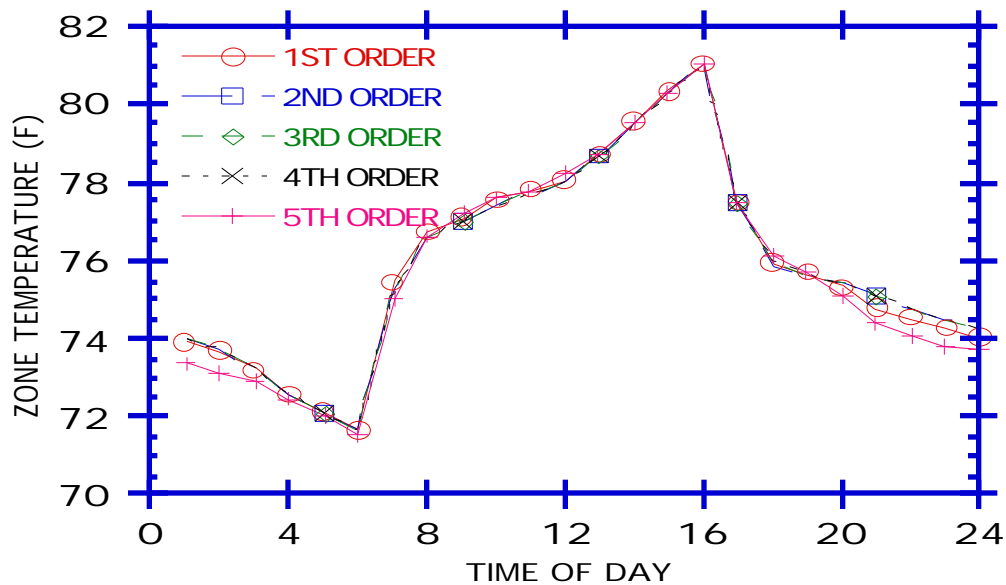


Figure 3a: Zone air temperatures as computed by the lagging with capacitance method using 1st, 2nd, 3rd, 4th, and 5th order approximations for the temperature derivative

## EFFECTS OF ORDER OF DERIVATIVE APPROXIMATION

1 ZONE, SUMMER DESIGN DAY, 0.25 HOUR TIME STEP

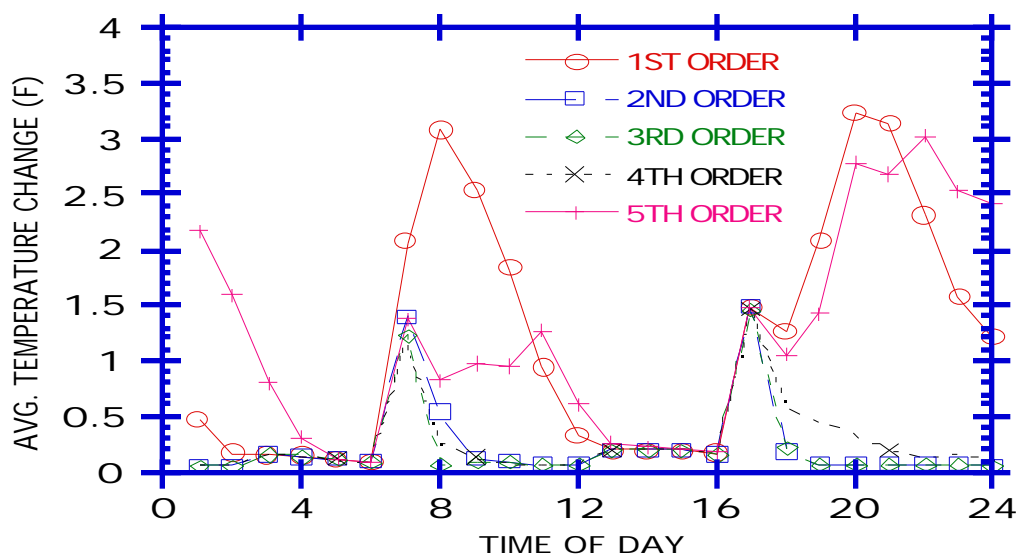


Figure 3b: Average change in zone air temperatures per time step as computed by the lagging with capacitance method using 1st, 2nd, 3rd, 4th, and 5th order approximations for the temperature derivative

## EFFECTS OF ORDER OF DERIVATIVE APPROXIMATION

1 ZONE, SUMMER DESIGN DAY, 0.25 HOUR TIME STEP

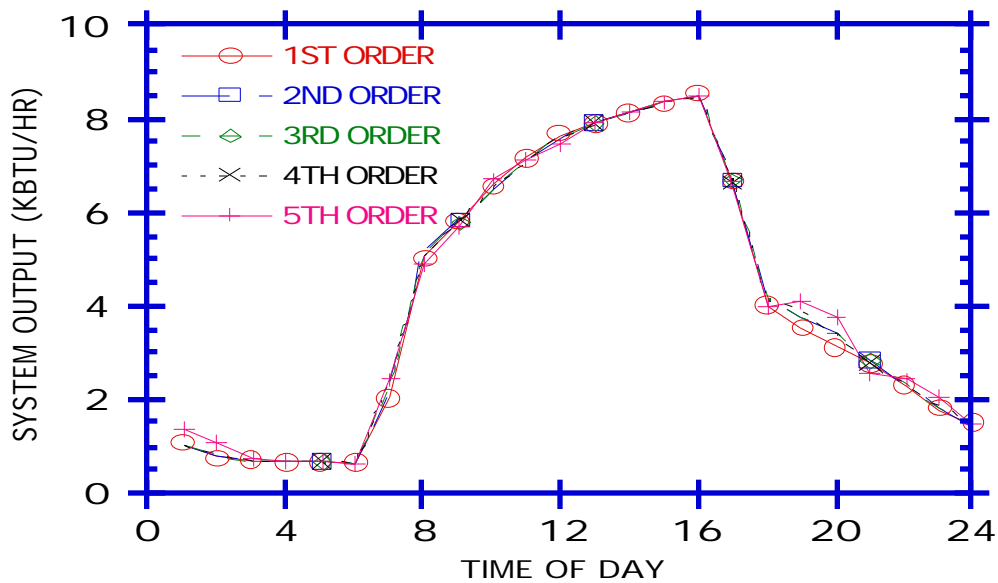


Figure 3c: Zone cooling loads as computed by the lagging with capacitance method using 1st, 2nd, 3rd, 4th, and 5th order approximations for the temperature derivative

## EFFECT OF TIME STEP ON 3RD ORDER METHOD

1 ZONE, SUMMER DESIGN DAY, ZONE TEMPERATURE

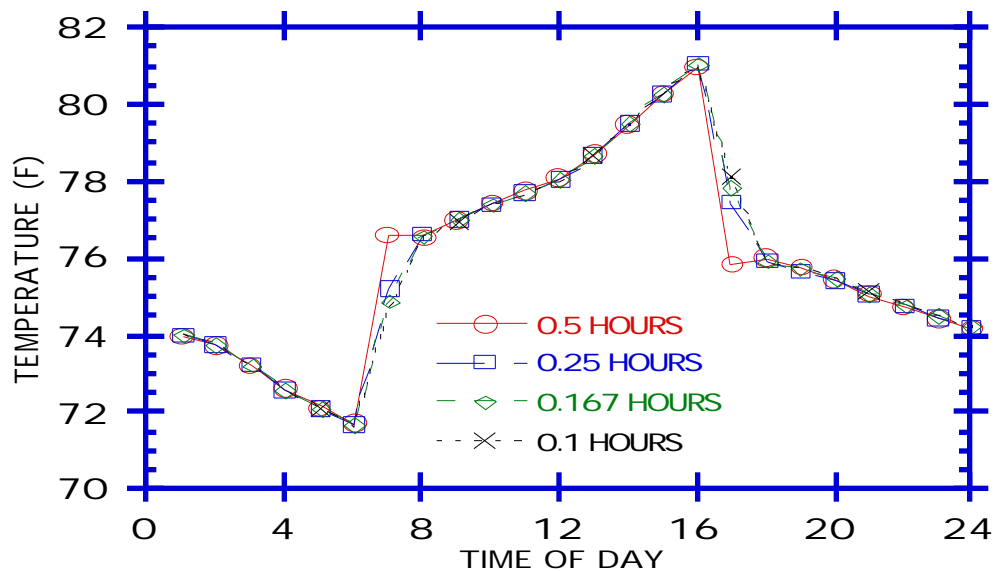


Figure 4a: Zone air temperatures as computed by the 3rd order lagging with capacitance method at time steps of 1/2, 1/4, 1/6, and 1/10 hours.

## EFFECTS OF TIME STEP ON 3RD ORDER METHOD

1 ZONE, SUMMER DESIGN DAY, AVG. TEMP. CHANGE

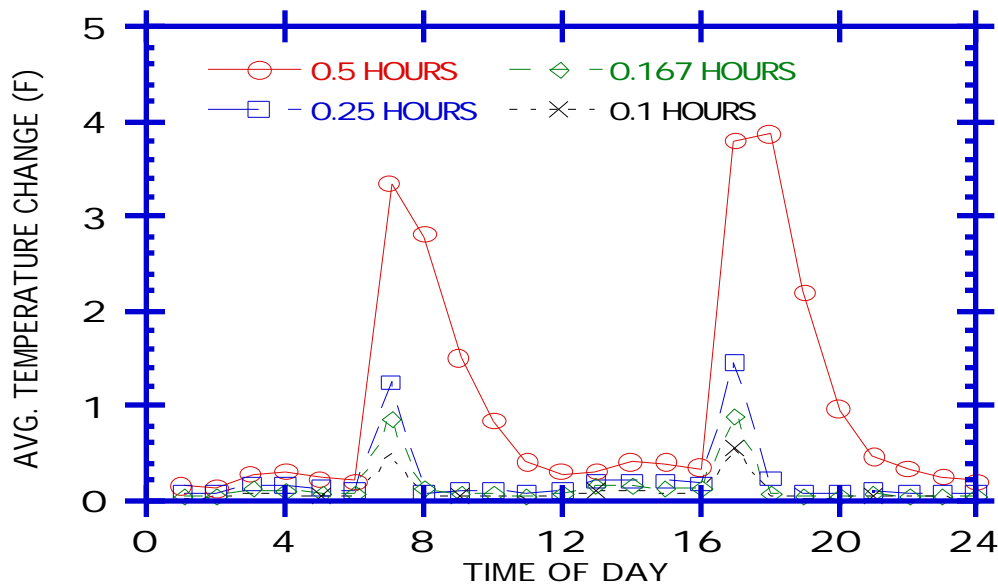


Figure 4b: Absolute value of the average temperature change per time step for the 3rd order lagging with capacitance method at time steps of 1/2, 1/4, 1/6, and 1/10 hours.

## EFFECT OF TIME STEP ON 3RD ORDER METHOD

1 ZONE, SUMMER DESIGN DAY, COOLING LOADS

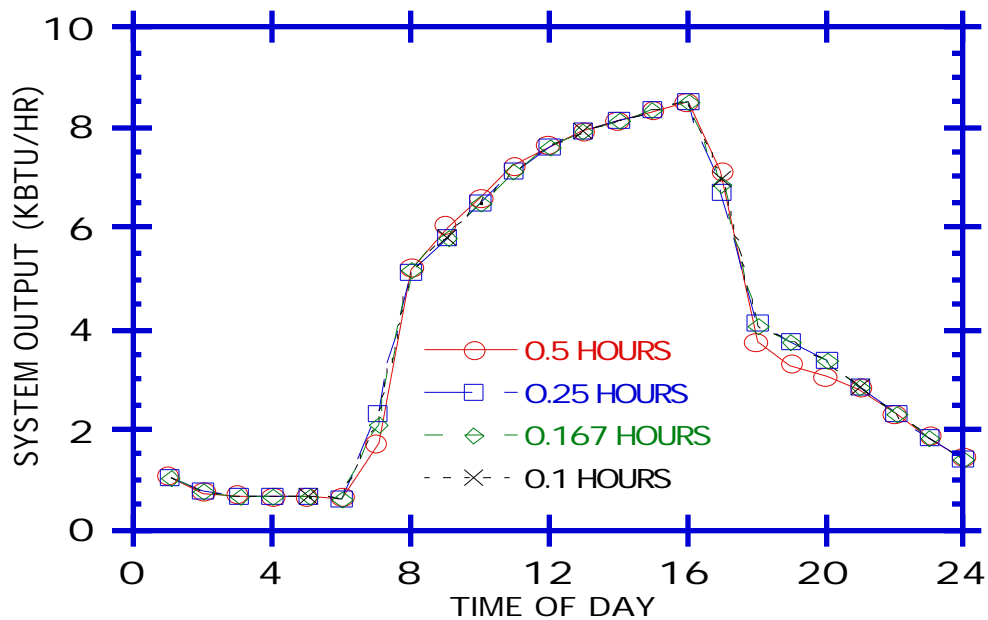


Figure 4c: Zone cooling loads as computed by the 3rd order lagging with capacitance method at time steps of 1/2, 1/4, 1/6, and 1/10 hours.

Finally, we are interested in the effects of the new methods on computation time as compared to the current BLAST program. Table 2 compares BLAST and the lagging with capacitance method for buildings consisting of 1, 3, 5, and 10 zones. The table shows the total number of loops through the heat balance equation for a typical design day run. Design day runs are performed by repeating the same daily cycle of conditions until the temperature history converges. The results shown are for standard BLAST, the third order method using a time step of 15 minutes (which in all these test cases provided adequate accuracy), and the third order method using a time step of 6 minutes. As might be expected the combined method was strongly time step dependent: however, the building complexity, which was similar in all cases, did not affect the number of time steps required for all except the 10 zone case. For the 10 zone case the combined method converged using 96 and 240 fewer calculations for the 1/4 hour and 1/10 hour cases respectively. This corresponds to exactly one less day of simulation. The reasons for this reduction in simulation time are still unclear; however we suspect that the answer lies in the convergence checks performed at the end of each day's simulation. The number of iterations required for BLAST showed a strong dependence on the building complexity, fan system operation and internal load schedules. Although a significant downward trend in the number of iterations required was indicated as the number of zones was increased. As was noted above, this trend requires further analysis of the convergence checks performed by BLAST. Therefore while these test cases all show BLAST to make fewer computations than the combined method it is by no means guaranteed that this will always be the case.

Method	Number of zones simulated			
	1	3	5	10
BLAST	303	219	164	175
combined BLAST 3rd order, 0.25 hour	384	384	384	288
combined BLAST 3rd order, 0.1 hour	960	960	960	720

Table 2: Iterations required to converge BLAST and combined method for a summer design day

## VI. CONCLUSIONS

In this paper we have specifically explored the implementation of noniterative methods into heat balance based energy analysis using a combined building and system simulation. Our efforts have concentrated on three distinct methods: finite difference, lagging of the system response by one time step, and lagging including the effects of zone air capacitance. Our results show that the lagging with capacitance method provides the best results in terms of stability of the simulation without requiring a prohibitively small time step. By this we mean keeping computation time short enough to be compatible with use on personal computers. Additionally, by using a third order approximation for the derivative term in the energy balance equation the stability of the method is further enhanced allowing larger time steps to be taken.

There is no doubt that the combined simulation technique will, in general, take more computation time than the current BLAST simulation: however, significant benefits are gained by performing the simulation in this manner. Most important of these is that the effects of the air handling system on the conditioned space are computed directly, making it readily apparent to the user when conditions in the space exceed the proscribed limits. Additionally, the somewhat artificial control profile which is currently used to approximate the effect of the system on the zone is totally eliminated.

As yet no attempt has been made to complete the loop from the central plants to systems. It is in this area that future research effort will be directed.

## VII. REFERENCES

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